On the Nature of the Strong Emission-Line Galaxies in Cluster Cl 0024+1654: Are Some the Progenitors of Low Mass Spheroidals? [1]

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Abstract

We present new size, line ratio, and velocity width measurements for six strong emission-line galaxies in the galaxy cluster, Cl 0024+1654, at redshift $z \sim 0.4$. The velocity widths from Keck spectra are all narrow ($30 \lesssim \sigma \lesssim 120$ km s^{-1}), with three profiles showing double peaks. Four galaxies have low masses ($M \lesssim 10^{10} M_{\odot}$). Whereas three galaxies were previously reported to be possible AGNs, none exhibit AGN-like emission line ratios or velocity widths. Two or three appear as very blue spirals with the remainder more akin to luminous H-II galaxies undergoing a strong burst of star formation. We propose that after the burst subsides, these galaxies will transform into quiescent dwarfs, and are thus progenitors of some cluster spheroidals [3] seen today.

Subject headings: galaxies: formation — galaxies: clusters:individual(cl0024+1654) — galaxies: evolution — galaxies: fundamental parameters — cosmology: observations

[3]We adopt the nomenclature suggested by Kormendy & Bender (1994), i.e., low-density, dwarf ellipsoidal galaxies like NGC 205 are called 'spheroidals' instead of 'dwarf ellipticals'.

1. Introduction

Photometry in two distant clusters of galaxies by Butcher and Oemler (1978) revealed a surprisingly large population of blue galaxies (Butcher-Oemler effect). Follow-up spectroscopy by Dressler and Gunn (1982, 1983 [DG83]) and Dressler, Gunn, and Schneider (1985 [DGS]) were pioneering steps towards confirming cluster membership and unraveling their nature from spectral lines. Among six blue galaxies observed in 3C 295, three appeared to be active galactic nuclei (AGN) and three to have strong Balmer absorption lines and negligible emission lines suggestive of a burst of star formation (DG83). Among 14 blue members observed in Cl 0024+16, three also appeared to be AGNs, but the remaining resembled local spirals with extended star formation, rather than starbursts as in 3C295 (DGS).

Since their line-ratio criterion for AGNs was not foolproof and their spectra were of low spectral resolution (over 1000 km-s^{-1}), DGS suggested that linewidths would be a useful check of their claimed AGNs. This *Letter* presents such linewidths as well as new line ratios and results of searches for blue compact nuclei for all three AGN candidates in Cl 0024+1654 as well as for three other emission line galaxies. None are confirmed to be AGNs. We adopt $h = 0.5$, $q_0 = 0.05$, and $\Lambda = 0$, i.e., $\Omega_0 = 0.1$, as our cosmology. Given these parameters, L^* ($M_B \sim -21$) corresponds to $r \sim 21.0$ and $1''$ spans 7.0 kpc at the cluster redshift of $z = 0.4$.

2. New Observations

Six galaxies are in our sample and all (except SDG 146) are among the bluest galaxies in the cluster (see colors in Table 1). Five are those with the largest [O II] equivalent widths among the 14 blue cluster members studied by DGS. The remaining galaxy (SDG 173A) is

not in the catalogs of DGS; Schneider, Dressler, and Gunn (1986; SDG); or Dressler and Gunn (1992). For its identification, see Table 1 and Fig. 2 of Lavery, Pierce, and McClure (1992). It has been included because spectra taken with the Shane 3 m at Lick Observatory identified it as a cluster member with very strong [O II] emission (restframe equivalent width EW(O II) $\sim 94 \pm 10$ Å). Its emission line ratios (Table 1) would satisfy the definition of an AGN by Dressler, Thompson, and Shectman (1985), namely 1) EW(O II) > 3 Å; 2) EW(O III) or EW(Hβ) $\approx$ EW(O II) ; and 3) EW(O III) $>$ EW(Hβ).

The key observations for all six galaxies were taken on UT 1994 October 3 and 4, using the HIgh Resolution Echelle Spectrograph (HIRES; Vogt *et al.* 1994) at the W. M. Keck 10 m Telescope under $\sim 0\farcs8$ (FWHM) seeing. The $1\farcs15 \times 14''$ slit yielded a FWHM spectral resolution of 2 pixels or 8 km s^{-1} on the Tektronix 2048^2 CCD. All exposures were 1800s, except for SDG-231 which was observed twice. Internal quartz lamp frames for flatfields and Th-Ar arc lamp frames for wavelength calibration were taken after observing at each grating setting. The spectra were reduced using standard techniques described in the IRAF/NOAO "echelle" package [4]. After flatfielding, cosmic rays removal, correction for scattered light and sky-subtraction, the central 5 pixels (i.e., $1''$) were coadded to produce 1-D spectra in velocity space. Four echelle orders spanning the rest wavelength region ∼3700–5100 Å were typically used to measure linewidths for the strongest emission lines. Although the velocity profiles are complex, we have, nevertheless, chosen σ (i.e., 0.425 FWHM) of a single Gaussian to characterize the widths. Such complex profiles are also seen in nearby dwarf amorphous galaxies by Marlowe et al. (1995).

For SDG 125 and SDG 173A, we acquired additional Keck spectra with the Low

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[4]IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation

Resolution Imaging Spectrograph (LRIS; see Oke et al. 1995) in the multislit mode. The detector was a Tektronix 2048^2 CCD (24 μm or 0.″215 pix^{-1}). We used a 900 l mm^{-1} grating blazed at 5000 Å covering 5200 - 7000 Å and a 1200 l mm^{-1} grating blazed at 7500 Å and covering 8500 - 9800 Å. With a slitwidth of 1.″23, these gratings yielded 0.96 Å pix^{-1} and 0.66 Å pix^{-1} and an instrumental resolution of $\sim$ 4 Å FWHM and $\sim$ 2.5 Å FWHM, respectively. The data taken on the clear nights of UT 1995 September 21 – 23, consist of 10,200s in the blue and 3600s in the red. Seeing was variable but was estimated to be about 0.″8 FWHM during most of the exposures. The spectroscopic reduction involved cosmic ray removal, wavelength calibration based on night-sky emission lines, and background sky subtraction. The slitlet for each target was treated as single, but relatively short (8″- 15″) "long-slit". The spectra for each galaxy are shown in Fig 1 (plate XXX).

For SDG146 and SDG183, lower resolution spectra were obtained on UT 1996 September 6 with the 2.5 m Isaac Newton Telescope at La Palma Observatory. The 235mm camera of the Intermediate Dispersion Spectrograph (IDS, see Terlevich & Terlevich 1989) was used with the R600 IR grating that yielded a dispersion of 1.7 Å pix^{-1} with a wavelength range of 8137 - 9862 Å. The detector was a Tektronix 1024^2 CCD (24 μm and 0.″7 pix^{-1}) and the slitwidth was 1.″9, giving a 3.4 Å FWHM resolution (2 pixels). The PA was selected to cover both objects simultaneously. Exposures totaling 4800s were obtained under good conditions with moderate seeing. The reductions are similar to that applied to the Keck LRIS spectra.

Sizes for four galaxies are based on archive WFPC-2 images (GO 5453; PI E. Turner) that were reduced, described, and kindly provided by Colley, Tyson, & Turner (1996). The stacked images total 8400s for exposures in the F450W filter (blue) and 6600s in the F814W (red). For SDG 125 and 223, R. Lavery kindly provided High Resolution Camera (HRCAM; McClure et al. 1989) images (2h V, 1h R) taken on the Canada France Hawaii

Telescope and used by Lavery et al. (1992). These 1024^2 SAIC CCD images have a scale of $0\farcs13$ pix^{-1}, a field of view 2.2' on a side, and a PSF FWHM of $\sim 0\farcs45$. For both the HST and HRCAM images (Fig. 1), fluxes measured through multiple circular apertures were used to measure half-light radii in the F814W or R filter.

3. Results

The key result is that the HIRES spectra show the strong emission lines to be very narrow (< 60 km-s^{-1}) for four galaxies and moderately narrow (~ 120 km-s^{-1}) for the remaining two (SDG 125 and 146). The line profile of SDG 125 shows, however, two components each having $\sigma \sim 55$ km-s^{-1}. SDG 173A and SDG 183 may also have such complex profiles. The HIRES data reveal that none of the six galaxies have the large widths expected for AGN's, though a weak, very broad component would be difficult to detect. For three AGN candidates (SDG 125, 173A, and 183), line ratios of Hα and [N II] versus [O III] and H_β from LRIS and IDS spectra are *inconsistent* with LINERS or Seyfert 2 galaxies (i.e., [N II]/H$_\alpha\times$ [O III]/H$_\beta > 2$), but do match those of H-II galaxies (Veilleux & Osterbrock 1987).

Besides spectra, another check for AGNs can be made by searching the *HST* and HRCAM images for bright, blue, compact nuclei. SDG 125 and 183 show no evidence for such nuclear components. The remaining AGN candidate, SDG 223, is so close in size to the PSF of the HRCAM images that this test is not reliable. By itself, this morphological evidence against the AGN hypothesis is not very compelling, since dust may obscure the presence of an AGN, but it strengthens the conclusions based on the HIRES kinematic and LRIS line-ratio data.

For our sample, Lavery et al. (1992) have already examined the HRCAM images for

morphology, with three noted to show the presence of a disk (SDG 125, 146, and 231), so the velocity widths reported above will be underestimates of their true values since these galaxies do not appear edge-on. SDG 173A is claimed to be a close interacting system; four (SDG 125, 146, 173A, and 231) show evidence for tidal tails or disturbed morphology, and one appears unresolved (SDG 223). The new *HST* images provide improved ($\sim 2\times$) resolution, with SDG 146 appearing to have a blue ring of star formation surrounding a central *red* nucleus; SDG 173A to be a very distorted system strongly suggestive of tidal disruption; SDG 183 to be a small face-on spiral with no bright blue nucleus; and SDG 231 to be an elongated, narrow galaxy with very blue colors and high surface brightness.

The half-light radii (Table 1) are also useful diagnostics. SDG 125, 146, and 183 appear to be spirals of normal size ($\sim$ 5 - 10 kpc in radius) while SDG 173A and 223 are only $\lesssim$ 3 kpc in size, which match that of dwarf galaxies rather than that of luminous (L^*) disk galaxies. SDG 231 appears to be highly elongated, so that the half-light radius derived from circular apertures is larger than a radius measured from isophotal boundaries, but smaller than the intrinsic one for an inclined disk.

4. Discussion and Conclusions

This project was motivated by the suggestion of DGS that three of the cluster members with the strongest [O II] emission lines in Cl 0024+1654 are AGN's. Based on the narrow velocity widths of Hβ and other emission lines as measured from HIRES, we conclude that neither of the two "certain Seyfert" candidates (SDG 125 and 223), nor the other "probable AGN" (SDG 183) are AGNs. Since the velocity widths for an AGN can be as narrow as $\sigma \sim 125$ km-s^{-1} (de Robertis and Osterbrock 1986), SDG 125 ($\sigma \sim 110$ km-s^{-1}) might still qualify as an AGN, particularly since no inclination corrections were applied. We have, however, additional evidence that SDG 125 is not an AGN. First, the HIRES profiles show

two, roughly equal components that is uncharacteristic of known AGNs (D. Osterbrock, private communication). Second, we have secured additional Keck spectra with LRIS in the far red that yield line ratios of Hα to [N II] that, combined with [O III] and H_β ratios, are consistent with star-formation (Veilleux & Osterbrock 1987) rather than LINERs or AGNs. Third, the entire galaxy appears very blue, with no evidence from HRCAM images for a bright, bluer, nuclear component. SDG 173A, though not in the original sample of DGS, qualifies as a possible AGN on the basis of the DGS criterion. Except for the additional evidence of a complex morphology that suggests an interaction (Lavery et al. 1992), the other arguments against SDG 125 being an AGN also apply here to SDG 173A.

Since none of the proposed AGNs in Cl 0024+1654 have been confirmed with improved spectroscopy and imaging data, we conclude that the scenario of having more AGN activity among distant clusters (DGS) is in serious jeopardy. Those AGN candidates found in other clusters (Dressler and Gunn 1992) and without obvious broad emission lines should be re-examined before the AGN evolution picture is accepted.

So what is the nature of these cluster galaxies with very strong emission lines? As already discovered in *HST* images by Dressler et al. (1994), the blue galaxies are *not* early-type spirals or large-bulge galaxies as originally suggested by DGS. This result argues against the traditional view that the blue galaxies seen as the Butcher-Oemler effect will become the S0's of today (DGS). Instead, many appear to be late-type spirals and irregulars as well as morphologically disturbed, possibly interacting or merging systems. One attractive physical mechanism for providing such morphologies has been suggested by Moore et al. (1996). Their simulations show that disk galaxies in clusters may become morphologically disturbed due to being "harrassed" by the gravitational potential of the cluster and other nearby galaxies. But a major unanswered question is the nature of the descendents of these galaxies.

Given the compelling evidence that we are observing very intense bursts of star formation rather than AGN activity among several of the bluest cluster galaxies, we suggest an alternative explanation: the very blue, luminous, cluster galaxies with small sizes and very low velocity widths are not massive galaxies, but *low-mass dwarfs* in a bursting phase (Babul and Rees 1992). The bursts in such dwarfs would be so intense that any remaining gas would be heated, expelled from the galaxy, and then stripped during interactions with the ambient cluster gas, thus destroying gas that might have the potential to fuel future star formation (Babul and Rees 1992). For example, adopting the energy input estimates for a starburst by Heckman et al. (1993), SDG 223 is releasing through star formation (Table 1) roughly 10× its binding energy. These galaxies are thus excellent candidates to be the progenitors of cluster spheroidals.

Indeed, recent *HST* and Keck HIRES observations of a sample of compact, narrow emission line galaxies (CNELG) in the field have revealed luminosity, size, color, line-ratio, kinematic, and morphological characteristics (Koo et al. 1994, 1995; Guzmán et al. 1996) virtually identical to that seen for several of the cluster galaxies in the current sample. These CNELGs have redshifts in the range $0.1 \lesssim z \lesssim 0.7$ and are thus seen at lookback times directly comparable to that of Cl 0024+1654 at $z \sim 0.4$.

The connection of the CNELGs and current sample with low-mass dwarfs is directly visible in a size versus velocity width diagram (Fig. 2). First note that the masses for SDG 173A, 183, 223, and 231 are in the range of low-mass dwarfs, i.e., $\lesssim 10^{10} M_{\odot}$, but we caution that SDG 183 may be a face-on spiral so that its narrow linewidth may in part be due to its low inclination rather than low-mass. Second, this diagram has no luminosity, and can thus be used to compare different galaxy types, independent of luminosity evolution. With surface brightness and fading taken into account, SDG 231 and 223 are the best counterparts to the CNELGs (see Fig. 4 in Koo et al. 1995 and columns 7 and 8 in

Table 1). Third, the likely counterparts in mass, size, and velocity widths to both the CNELGs and the current sample are either irregulars or spheroidals (such as NGC 205 rather than very low-luminosity dwarf spheroidals like Carina). Whereas spheroidals have metallicities and star formation histories that are fully consistent with a major intense burst of star formation (Skillman and Bender 1995), irregulars show a more subdued history (see Guzmán et al. 1996 for fuller discussion and references; see also recent evidence for high [O/Fe] abundances in planetary nebula for spheroidals that do not match that seen in irregulars and which suggest a briefer burst of star formation [Richer, McCall, and Arimoto 1996]).

Thus, following arguments favoring CNELGs to be the progenitors of local *field* spheroidals, we suggest that some of the blue galaxies seen in distant clusters are the progenitors of the numerous *cluster* spheroidals found today. Let us make a very rough estimate of the expected number density of cluster spheroidals with masses about $10^9 - 10^{10} M_\odot$ formed through these intense bursts. First we assume that the bursting phase lasts only a few 10^7 years and that the frequency of bursting dwarfs in clusters remains constant over a several Gyr period. In this case, and making the further crude assumption that the current spectroscopic sample of two or three is but 10% of the entire cluster sample of bursting dwarfs to fainter limits, we may easily obtain a factor of 1000 for the conversion of observed dwarfs in the burst phase to eventual descendents. This translates our sample of two or three [5] bursting galaxies to many hundreds to several thousand inert cluster spheroidals for Cl 0024+1654 by this time. Such large numbers of inert spheroidals are consonant with claims that 60% of the cluster galaxies brighter than $M_B = -14$ are spheroidals in both Coma (Bernstein et al. 1995) and Virgo (Binggeli, Tarenghi, and

[5]For two or three observed objects, the 95% Bayesian confidence limits on the underlying number densities are 0.30 and 7.95 objects (Kraft, Burrows, and Nousek 1991)

Sandage 1990). We thus find a rough, but consistent, link between the small numbers of bursting systems seen at a given moment in distant clusters and the large number of spheroidal descendents seen today.

In summary, new *HST* images and Keck echelle spectra of the six strongest emission line galaxies in Cl 0024+1654 show none to be bonafide AGNs. Instead, the evidence strongly favors the sample to contain spirals of normal sizes but active star formation as well as smaller, low-mass dwarf systems undergoing a major burst of star formation. With physical properties similar to those found in local H-II galaxies and more distant counterparts (CNELGs), the dwarfs are excellent candidates for being the progenitors of the numerous spheroidals seen in rich clusters at the current epoch.

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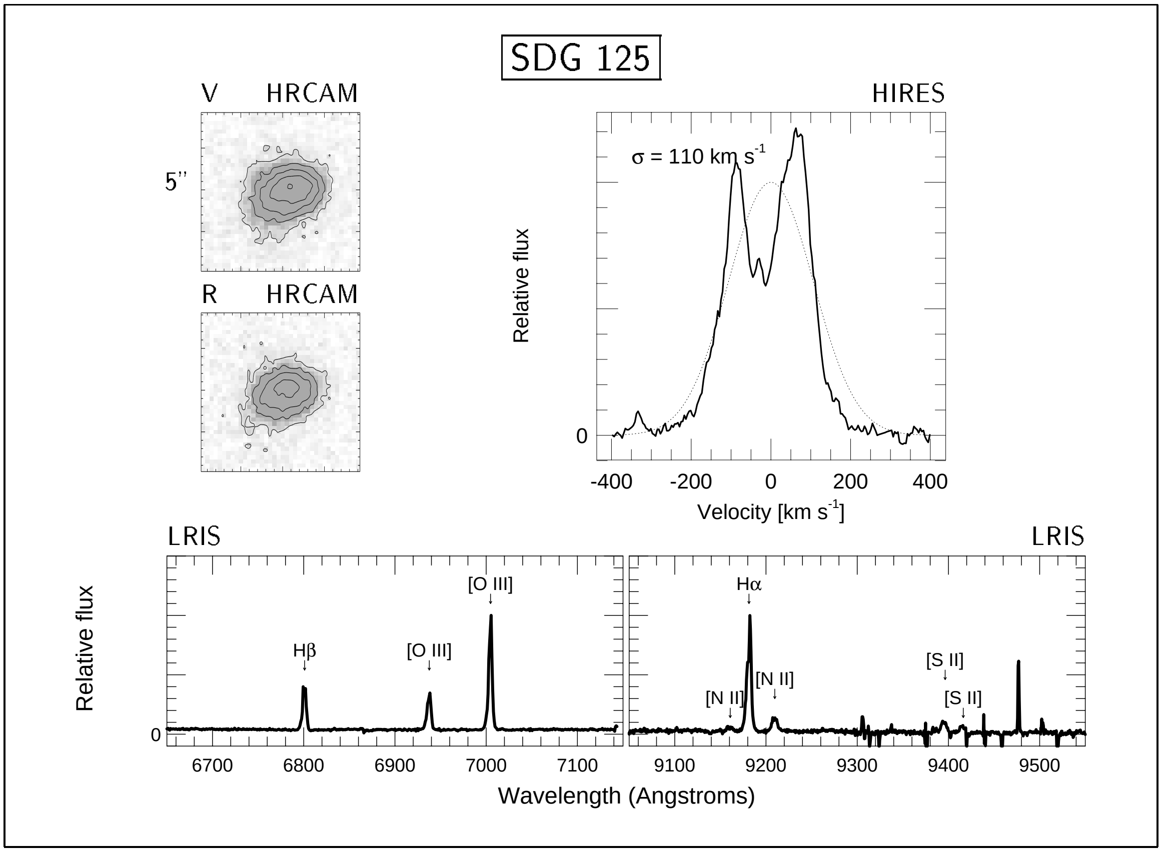
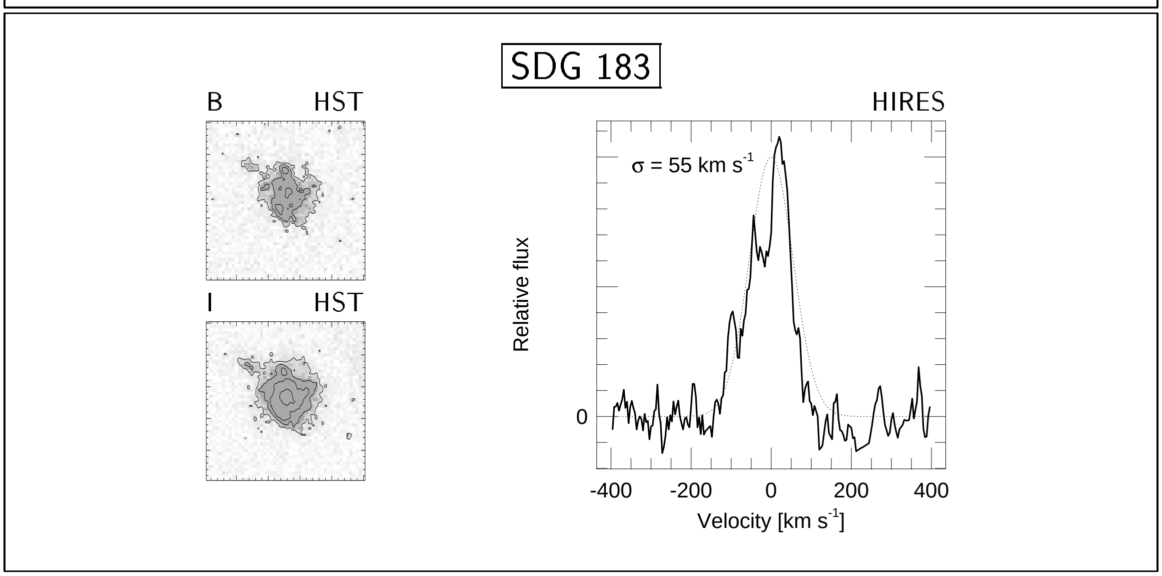
Figure Captions

FIG. 1. – a) Panel of *HST* images and Keck spectra for the three AGN candidates found by DGS in Cl 0024+1654. The images of SDG 125 in V and R were taken by Lavery et al. (1992) with HRCAM. The contours are spaced at intervals of 0.5 mag in surface brightness, beginning at 6 times the standard deviation of the local sky value above background. The Hβ and [O III] 5007 emission line profiles from the HIRES observations are shown with normalized amplitudes and in km s^{-1}. The instrumental resolution is $\sigma = 3.4$ km s^{-1}. The spectra below these are from two separate grating settings of LRIS that show the strengths of various emission lines and the lack of any broad emission component in the Balmer lines. For SDG 183, the B (F450W) and I (F814W) images were taken with WFPC-2. The images for SDG 223 are also from HRCAM. Dotted lines in the line profiles show the best Gaussian curve that fits the average of profiles from the measured emission lines. Note the clear presence of two components in SDG 125 and the hint of another component in SDG 183. The σ values are based on single Gaussian fits. b) Similar to a) for AGN candidate SDG 173A and two other strong emission line galaxies proposed to be spirals by DGS. All images are from WFPC-2.

FIG. 2. – The half-light radius (R_e) vs. velocity width (σ) diagram for the cluster and field samples of strong emission line galaxies. The large shaded pentagons are for the cluster spiral galaxies SDG 125, 146, and 183; the open pentagons are for the remaining galaxies SDG 173A, 223, and 231. The crosses are for local H-II galaxies from Telles (1995) and star symbols are for more distant CNELGs from Guzman et al. (1996). The typical locations of various other galaxy types are also shown, including E/S0 and spheroidals galaxies (Bender, Burstein & Faber 1992), spirals (de Vaucouleurs et al. 1991 - RC3), and irregulars (RC3). A few galaxies representative of today's evolved systems are identified. The dashed lines correspond to constant-masses of 10^8, 10^{10}, and $10^{12} M_\odot$.


SDG 125
V HRCAM
5''
R HRCAM
HIRES
σ = 110 km s-1
Relative flux
Velocity [km s-1]
LRIS
Hβ
[O III]
[O III]
Hα
[N II]
[N II]
[S II]
[S II]
Relative flux
Wavelength (Angstroms)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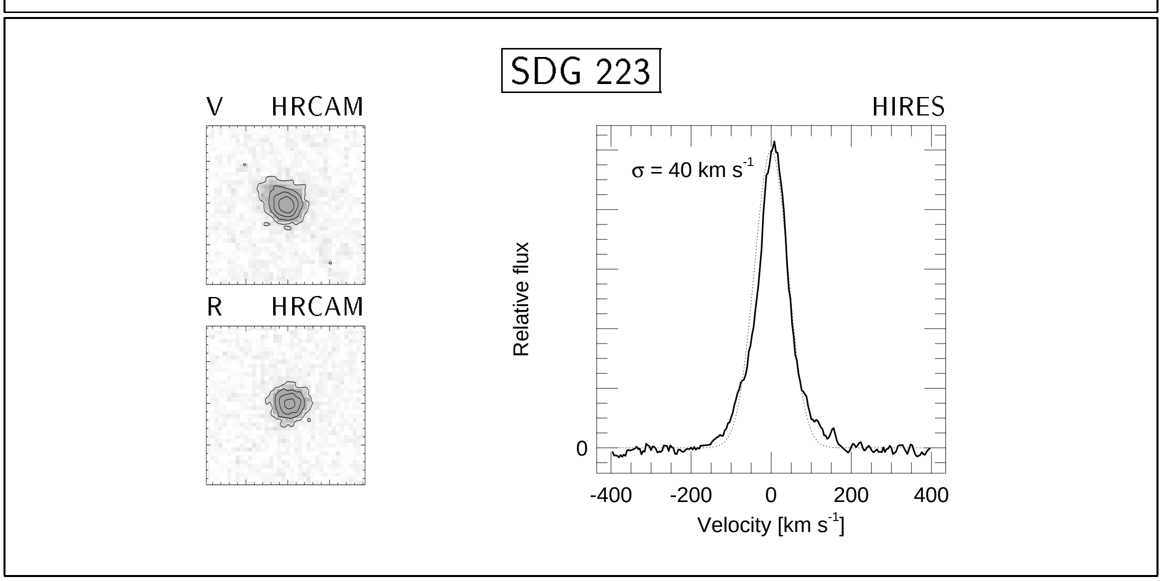
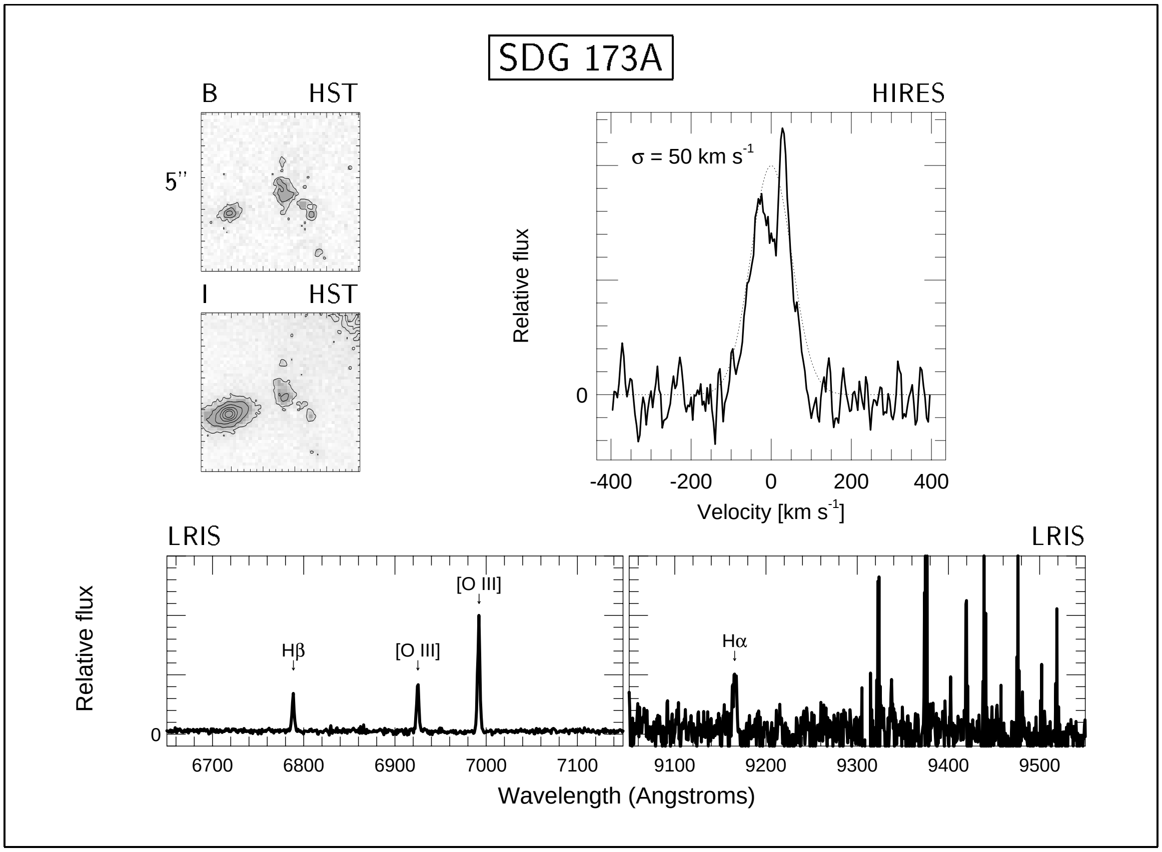
I HST
HIRES
σ = 55 km s-1
Relative flux
Velocity [km s-1]


SDG 223
V HRCAM
R HRCAM
HIRES
σ = 40 km s-1
Relative flux
Velocity [km s-1]


SDG 173A
B HST
5''
I HST
HIRES
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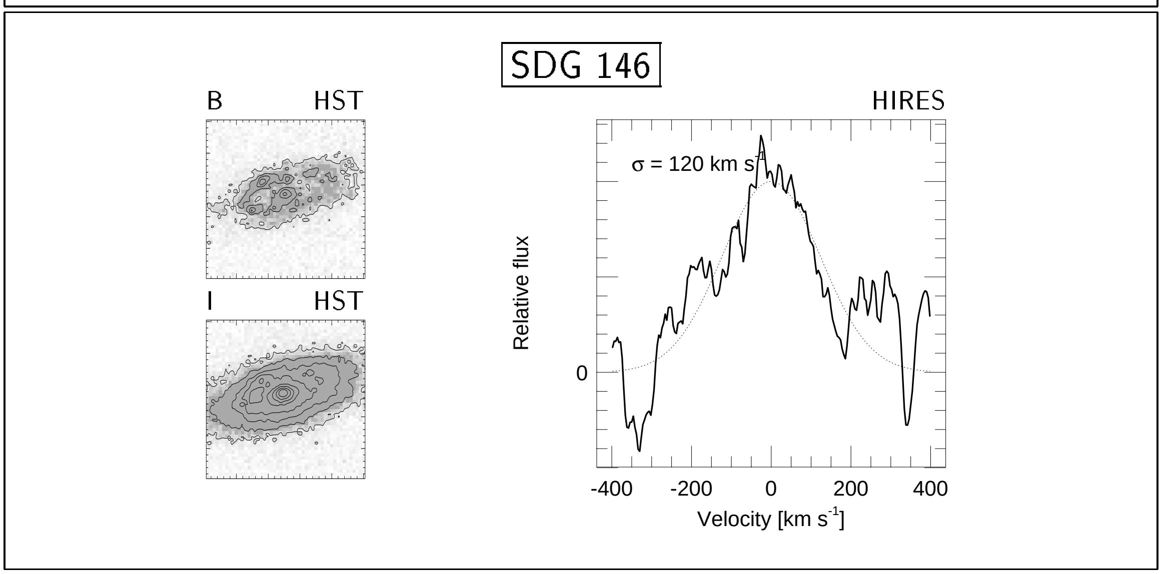
Relative flux
Velocity [km s-1]
LRIS
Hβ
[O III]
[O III]
Hα
Wavelength (Angstroms)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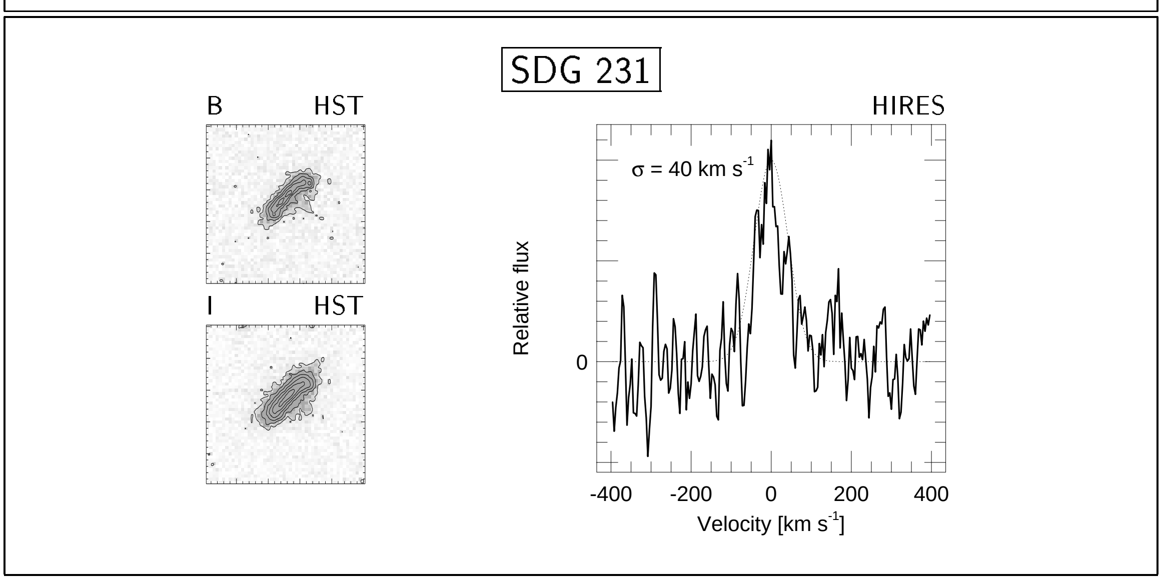
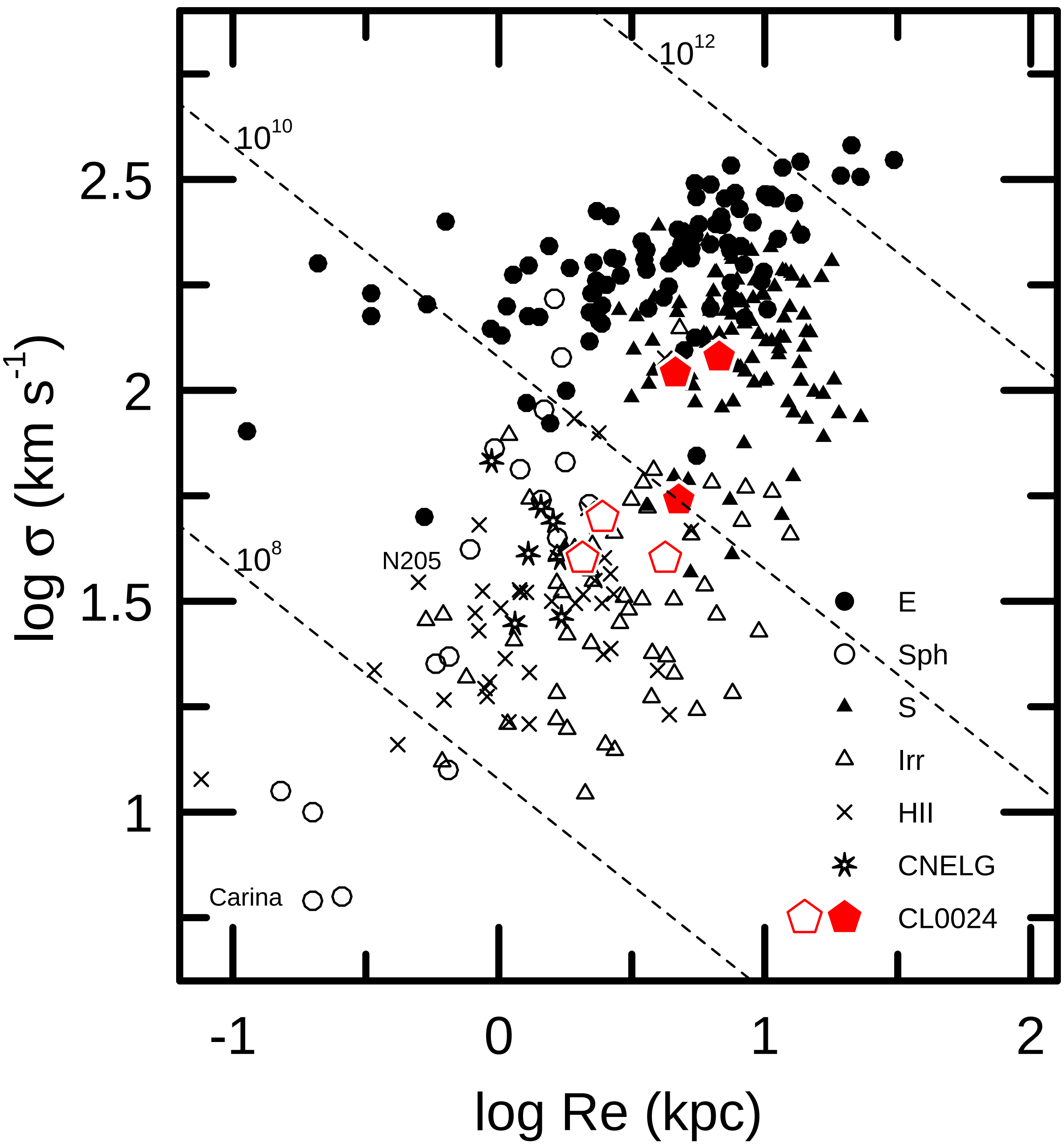
I HST
HIRES
σ = 120 km s-1
Relative flux
Velocity [km s-1]


SDG 231
B HST
I HST
HIRES
σ = 40 km s-1
Relative flux
Velocity [km s-1]



log σ (km s^{-1})
log Re (kpc)
2.5
2
1.5
1
-1
0
1
2
10^{12}
10^{10}
10^{8}
N205
Carina
E
Sph
S
Irr
HII
CNELG
CL0024

Table 1: Data for 6 Strong Emission-Line Galaxies in CL0024+1654

SDG (1)	z_{SDG} (2)	z (3)	Re (4)	r (5)	g-r (6)	M_B (7)	SBe (8)	[OIII]/Hβ (9)	[NII]/Hα (10)	$W_{[OII]}$ (11)	$W_{[OIII]}$ (12)	SFR (13)	σ (14)	M (15)	M/L (16)
125	0.399	0.3989	4.6	20.2	0.40	-21.6	20.0	2.3	0.16	78	107	13.6	110	6.6	1.0
146	0.392	0.4006	6.7	19.5	0.83	-22.0	20.7	2.5	0.50	25	6	6.3	120	11.4	1.2
173A	...	0.3996	2.4	23.5	0.3	-18.3	22.2	3.3	0.13	94	128	0.8	50	0.7	2.2
183	0.399	0.3994	4.7	21.1	0.22	-20.7	21.3	2.5	0.34	40	20	3.0	55	1.7	0.6
223	0.394	0.3996	2.1	21.4	0.23	-20.3	19.9	~ 5	...	126	~ 500	6.6	40	0.4	0.2
231	0.397	0.3989	4.2	21.0	0.22	-20.8	20.9	~ 1	...	38	~ 10	3.2	40	0.8	0.2

(1) SDG identification number; (2) Redshift measured by SDG; (3) Redshift measured in this work; errors are estimated to be $\sim$0.0003; (4) Half-light radius in Kpc; errors $\sim$15%; (5) Gunn r apparent magnitude from SDG; the value for SDG173A was measured by DCK from deep CCD images taken at KPNO; errors are estimated to be $\pm$0.2mag; (6) Gunn g-r colors from DGS; the value for SDG173A has been estimated from $B-R$; errors are estimated to be $\pm$0.25 mag; (7) Rest-frame absolute B magnitude; errors $\pm$0.4mag; (8) Rest-frame B-band surface brightness in magnitudes per square arcsecond; the uncertainty in these values is $\pm$0.6mag; (9) Observed excitation parameter [OIII]λ5007/Hβ (errors $\sim$10%); (10) Observed line ratio [NII]λ6584/Hα (errors $\sim$15%); (11) Equivalent width of [OII] in the rest frame in Å; (errors $\sim$15%); (12) Equivalent width of [OIII] in the rest frame in Å; (errors $\sim$15%); Values for SDG223 and SDG231 were estimated from figures 2 (DG) and 3 (DGS), respectively. (13) Star formation rate in $M_\odot$ yr^{-1}, derived from:
$SFR = 2.5 \times 10^{-12} \times 10^{-0.4(M_B - M_{B\odot})} EW([OII])$ (Guzmán et al. 1997); (14) Line width in km s^{-1} (errors $\sim$5%); (15) Mass in 10^{10} solar units, determined from $M = 3\ kG^{-1} R_e \sigma^2$ adopting a structural constant $k = 1.6$ (Guzmán et al. 1996); the uncertainty is estimated to be $\sim$10%; (16) Mass to light ratio in the B-band in solar units (errors $\sim$10%). We adopt H_0=50 km s^{-1} Mpc^{-1}, q_0=0.05, and Λ=0 for calculations.